Laser-initiated discharge produced plasma ablated from liquid metal electrodes

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ABSTRACT

Laser-initiated discharge produced plasma system has been studied as a viable approach for the EUV lithography light source at 13.5 nm wavelength. The source is based on a discharge in tin or galinstan vapor produced by laser pulse between rotating disk electrodes. This paper focuses on results of the computer modelling of that laser-induced discharge with electrical circuit characteristics and laser beam parameters similar to the used in the experiment. Z*-code comprising recent advances in atomic physics and radiation-magnetohydrodynamics is used under international collaborative project FIRE in the framework of FP7 IAPP to model laser- and discharge-produced plasma dynamics and emission. Complex consideration of radiation from unresolved transition arrays includes the model of non-equilibrium ionization in plasma of multicharged ions based on detailed kinetic equations resolution with major electon-ion interaction processes taken into account. The radiation-plasma dynamics and the spectral effects of self-absorption in laser produced plasma and discharge produced plasma are considered. The simulation results are compared with experimental data. The detailed physics of the effects taking place in the laser-initiated discharge is discussed.

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Radiation Sources for EUV Lithography

Diffraction restricts the resolution

$$r \geq k_1 \frac{\lambda}{NA}$$

NOW
EUV for HVM
beyond 16 nm

$\lambda \Rightarrow$ 13.5nm $\Rightarrow$ 6.Xnm
($h\nu$=92eV $\Rightarrow$ 185eV)

$\delta\lambda/\lambda \Rightarrow$ 2%

The optics is made of
multi-layer mirrors
with reflection efficiency ~70%

- For HVM: >> 200 W of in-band power at IF within < 3mm^{2}sr etendue
- For mask inspections ABI$\rightarrow$AIMS$\rightarrow$APMI : 30 $\rightarrow$ >100 W/mm$^2\cdot$sr

Sn, Xe… High energy density plasma (T_e=20-40eV) radiates at EUV range

LPP & DPP

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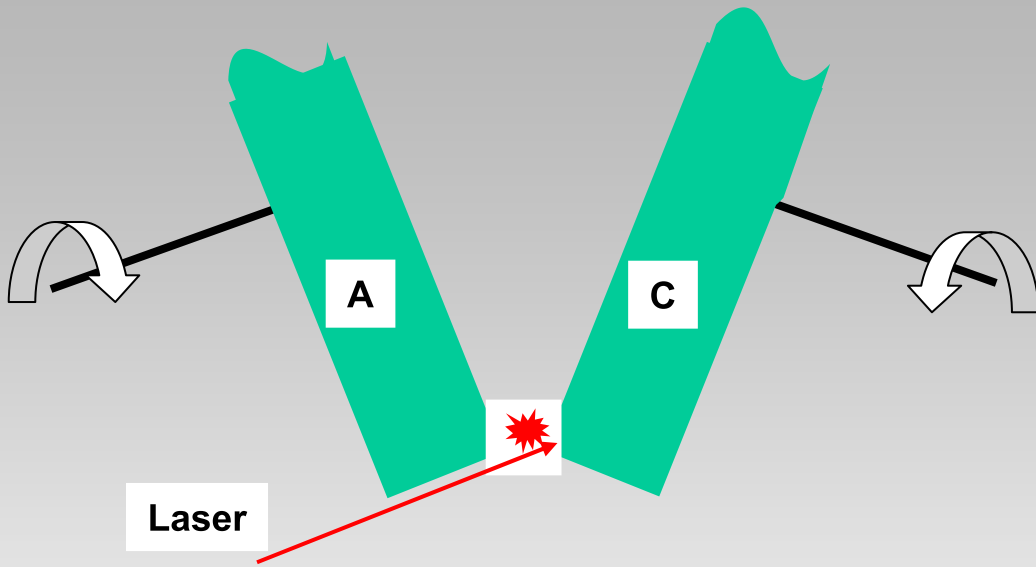
Laser Assisted Vacuum Arc (LAVA-lamp)



High-current discharge between two rotating electrodes covered with a thin liquid Tin or Galinstan film is triggered by local laser ablation of electrode material.

Discharge

capacitance	0.4 μF
inductance	19 nH
voltages	3 – 6 kV
energies	1.8 – 7.2 J
current	20 kA at 4.5 kV

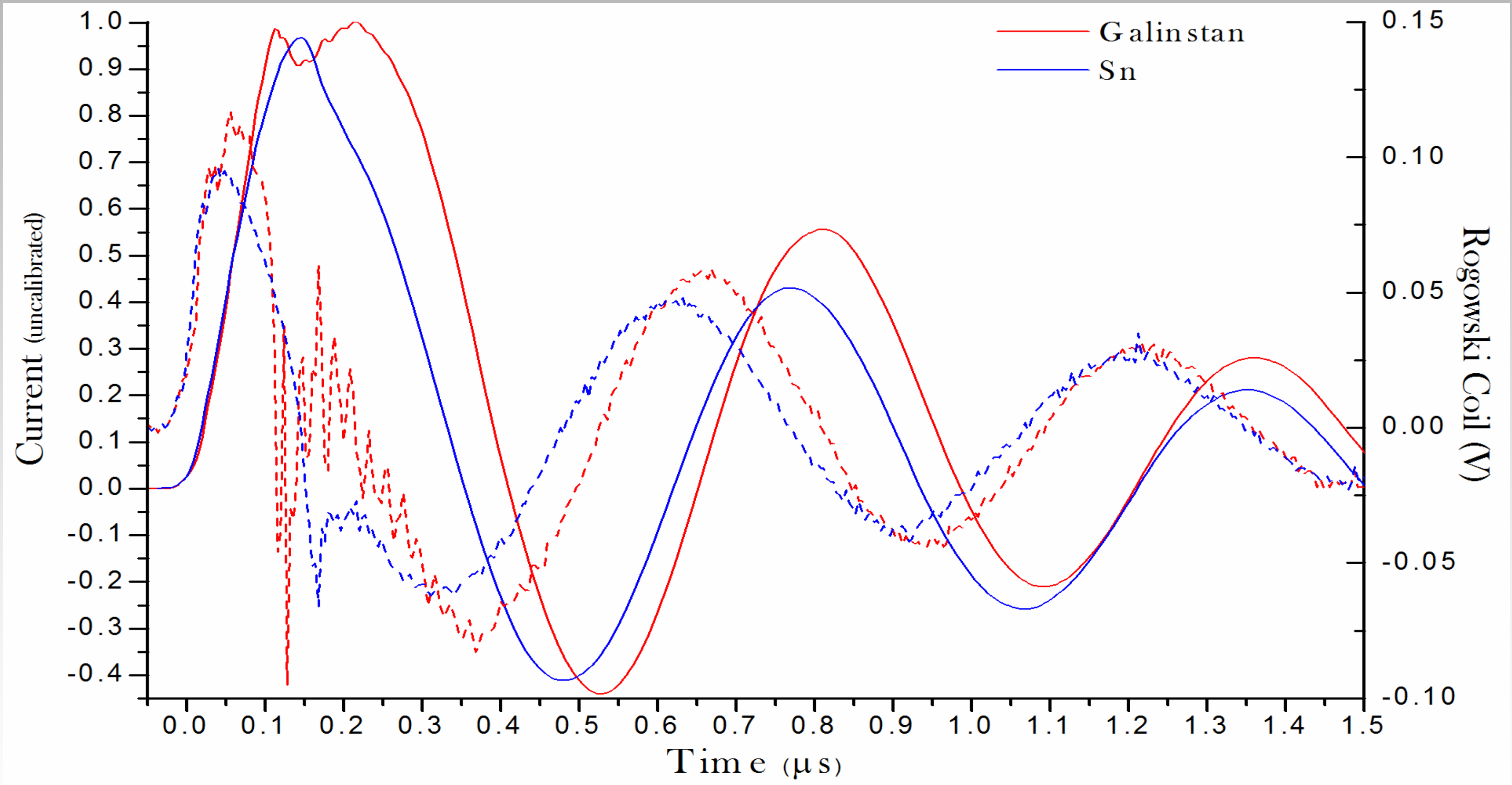
Trigger laser:

wavelength	1064 nm
beam diameter	3 mm
focal lens	30 cm
energy	5 – 50 mJ

(varied by means of rotatable half-wave plate and polarizing beam splitter)

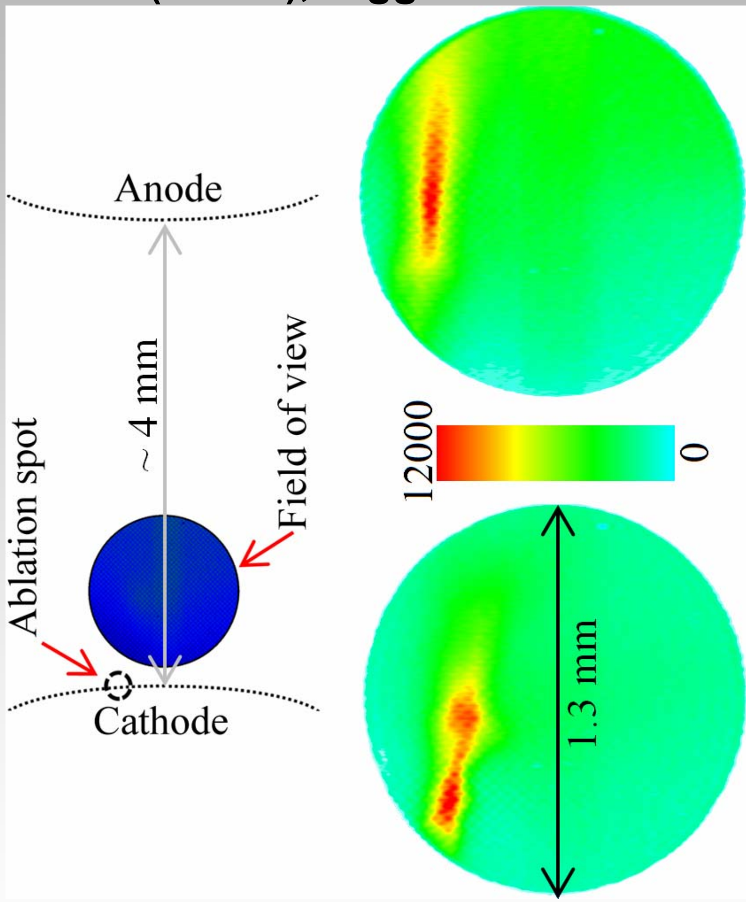
Pinching peqularity on the current

Rogowski coil current characteristics



EUV images of galinstan plasma pinch

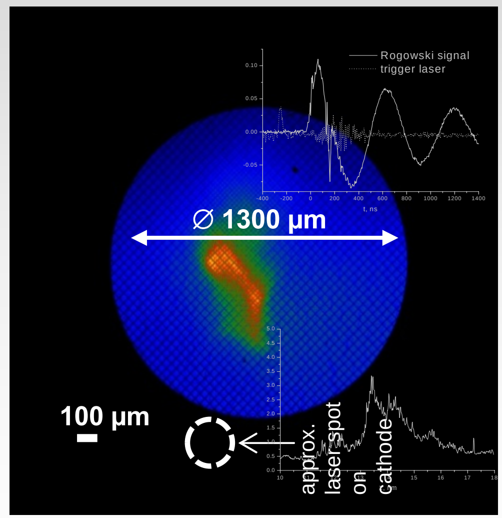
4 J (4.5 kV), trigger laser 5 mJ

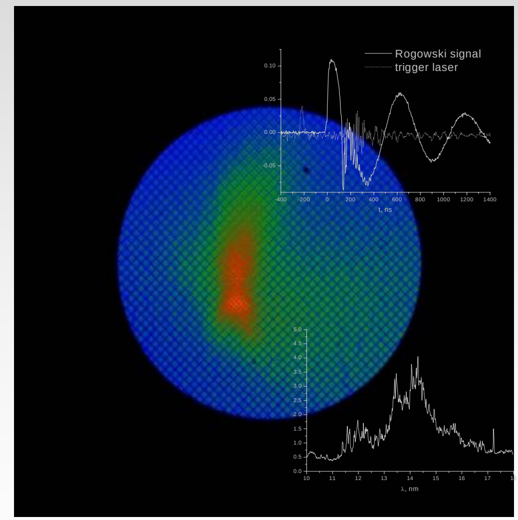


V_p65_64

Main pinching is near the cathode.
The EUV source size is of 100µm diameter.

In Galinstan the pinch is not stable.





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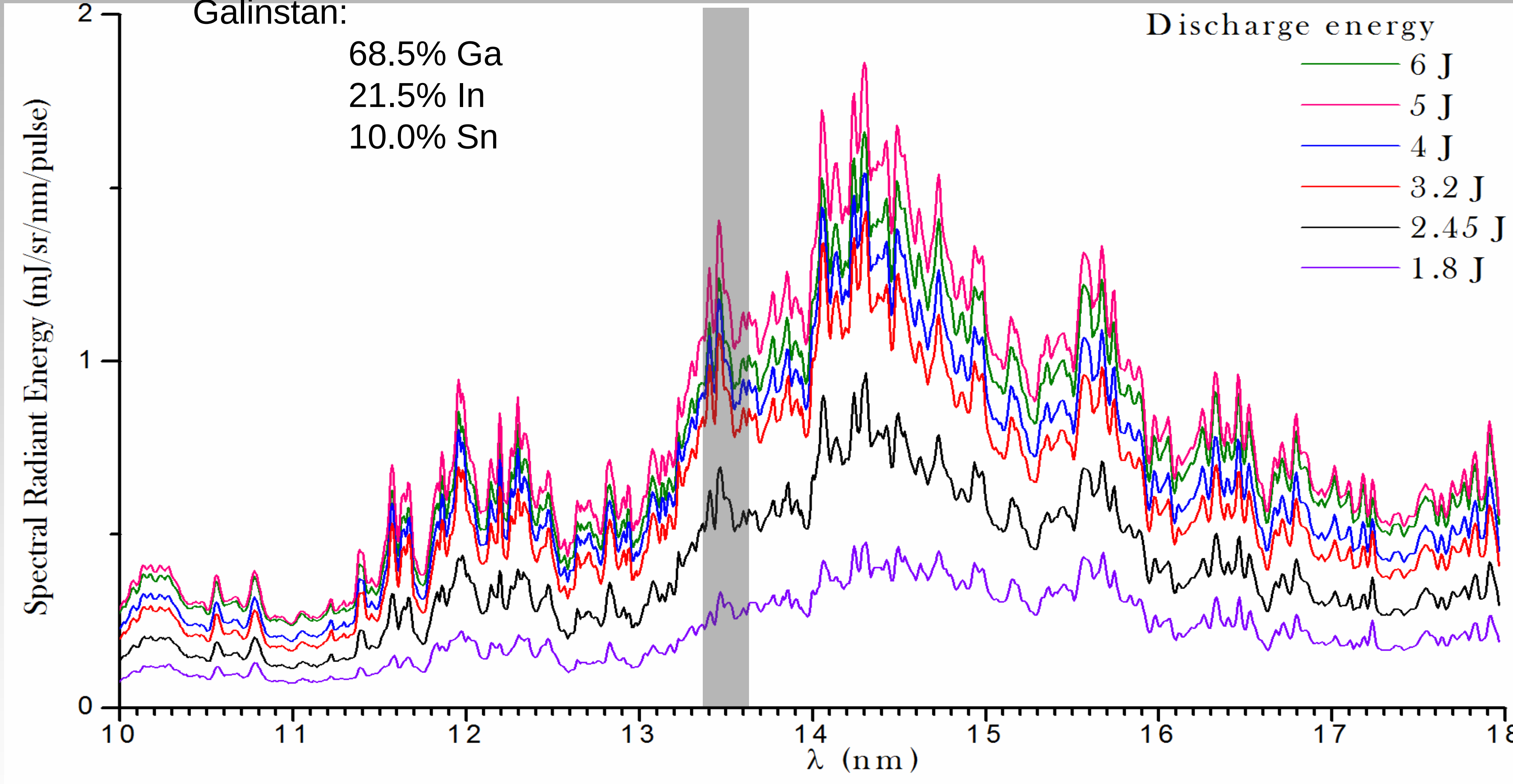
2012 International Workshop on EUV and Soft X-Ray Sources
Dublin, Ireland
October 8-11, 2012

EUV spectra for various discharge energies



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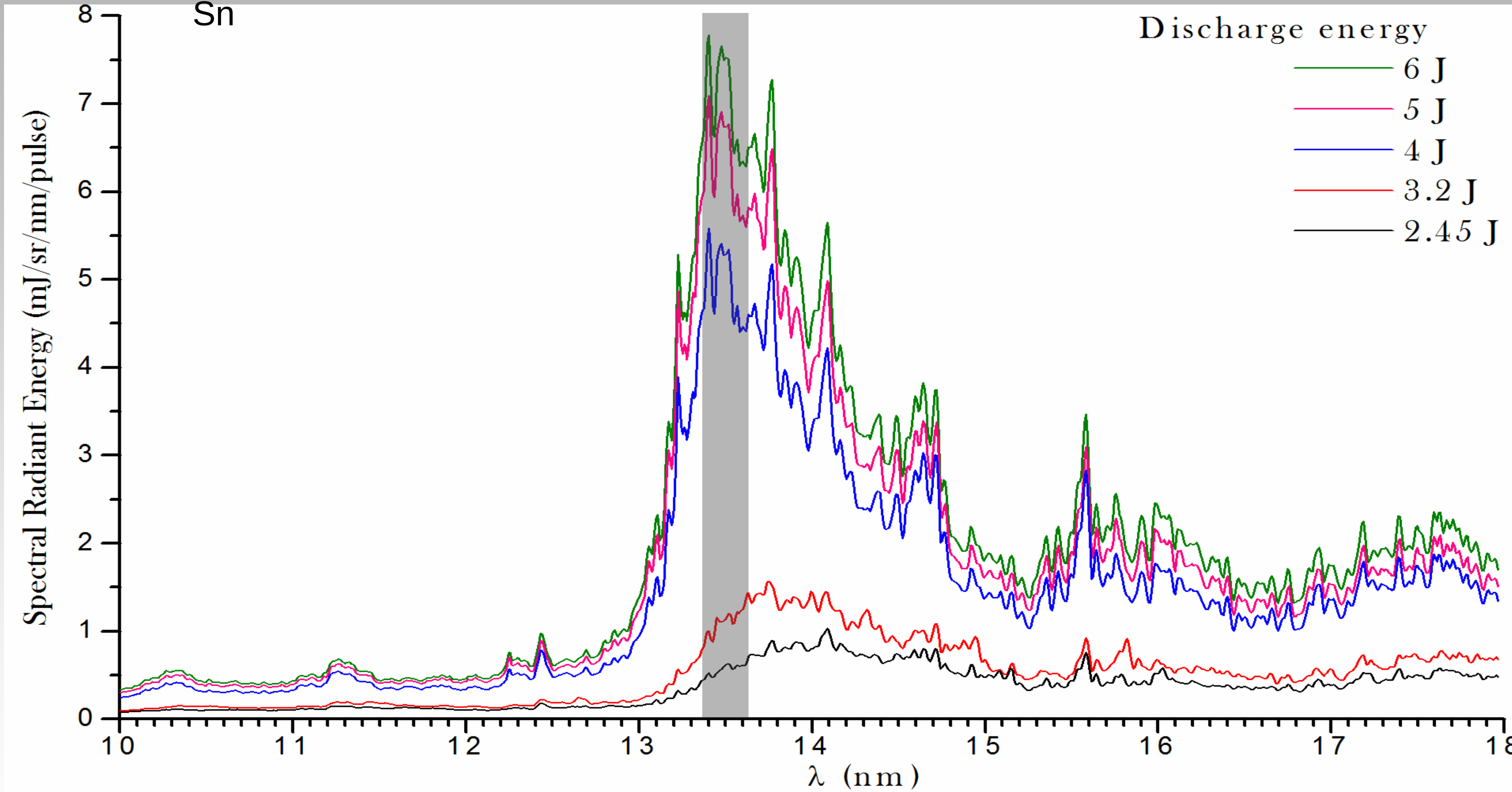
EUV spectra for various discharge energies



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ZETA → Z^* RMHD Code → Z^* BME → Z^+

multi-physics model

TABLES
nonLTE atomic & spectral data
(Te,ρ,U)

RMHD (2D, 3D) with:
- spectral multigroup radiation transport in nonLTE;
- nonstationary, nonLTE ionization;
- sublimation – condensation;
- energy supply (electric power, laser)
- etc

EMHD or 3D PIC with:
ionization of weekly ionized plasma, discharge triggering

Discharge plasma simulation in real geometry
Laser plasma

Data output:
r,z,*v*,$T_{e,i}$,ρ,*E*,*B*,Z,U_{ω}, etc;
visualization

Spectral postprocessing

Heat flux postprocessing

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Next Generation Modelling Tools

knowledge transfer FP7 IAPP project FIRE

- FIRE - European FP7 Industry-Academia Partnerships and Pathways project

- The FIRE project aims to substantially redevelop the Z* code to **Z⁺** to include improved atomic physics models and full 3-D plasma simulation of

  ✓ plasma dynamics
  ✓ spectral radiation transport
  ✓ non-equilibrium atomic kinetics with fast electrons
  ✓ transport of fast ions/electrons
  ✓ condensation, nucleation and transport nanosize particles.

- Modelling is essential in parametric scans in radiat source optimization, in fast particles and debris generation to solve current EUVL source problems as well as extending their application.

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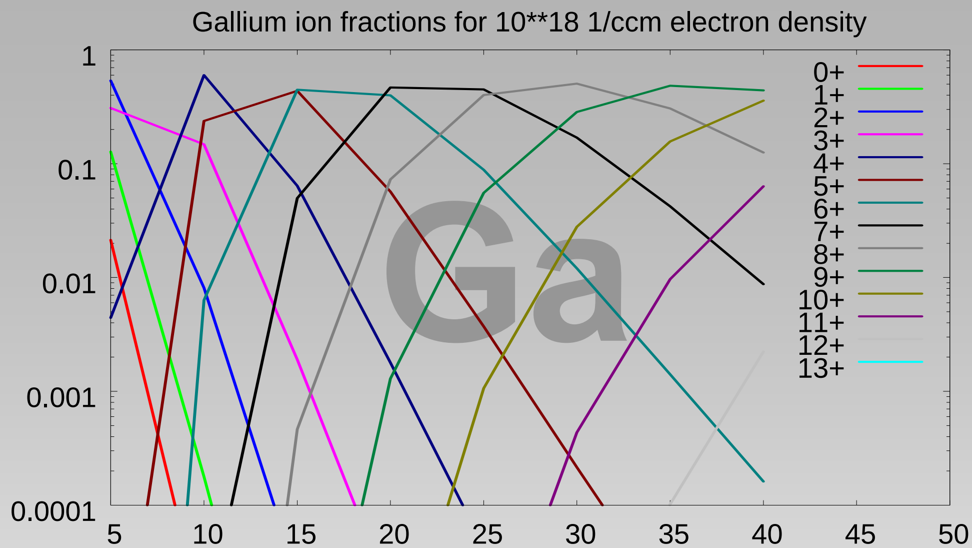
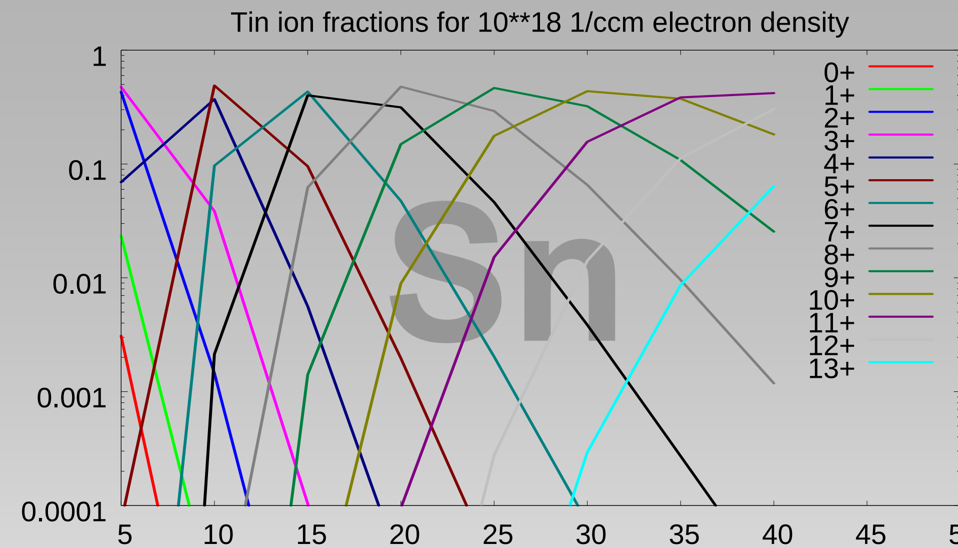
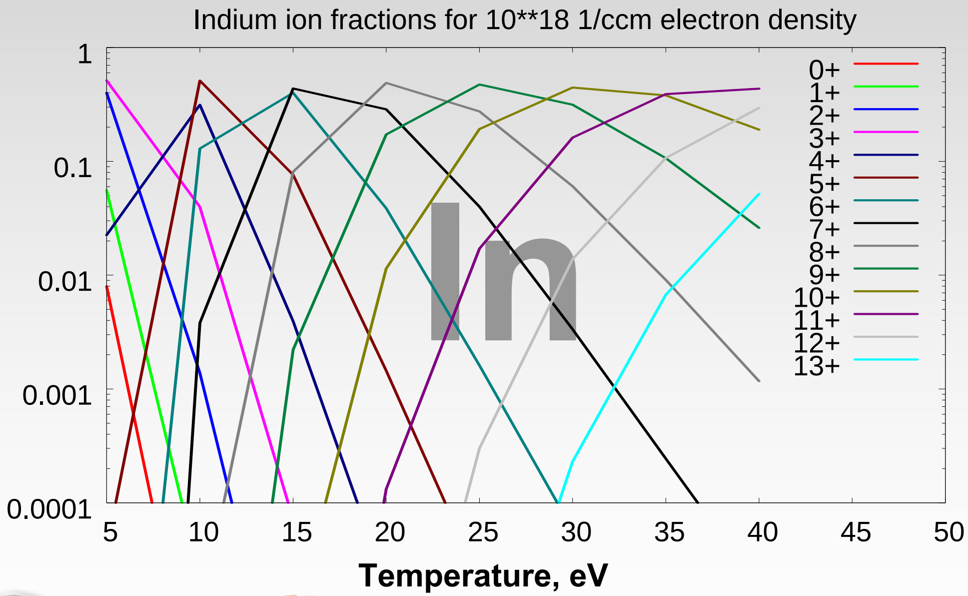
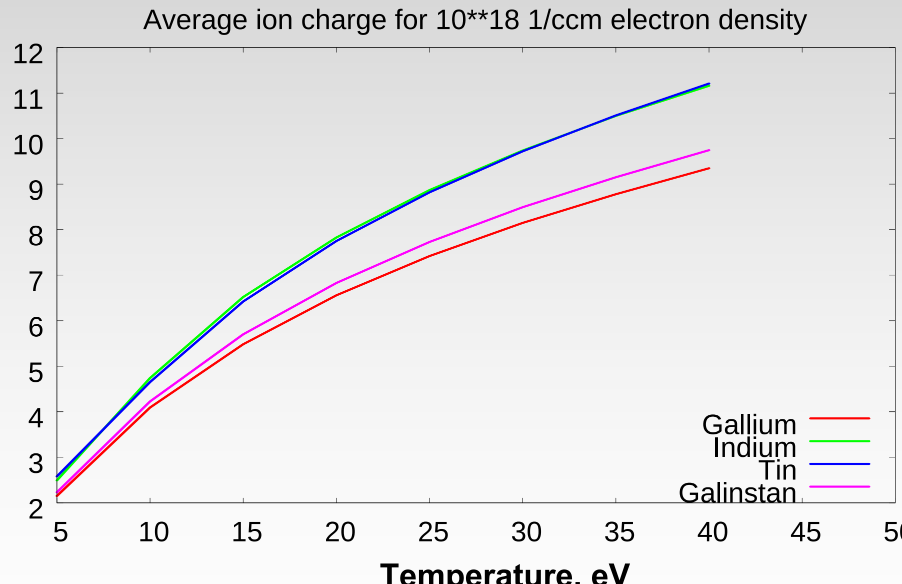
Ion fractions and average charge









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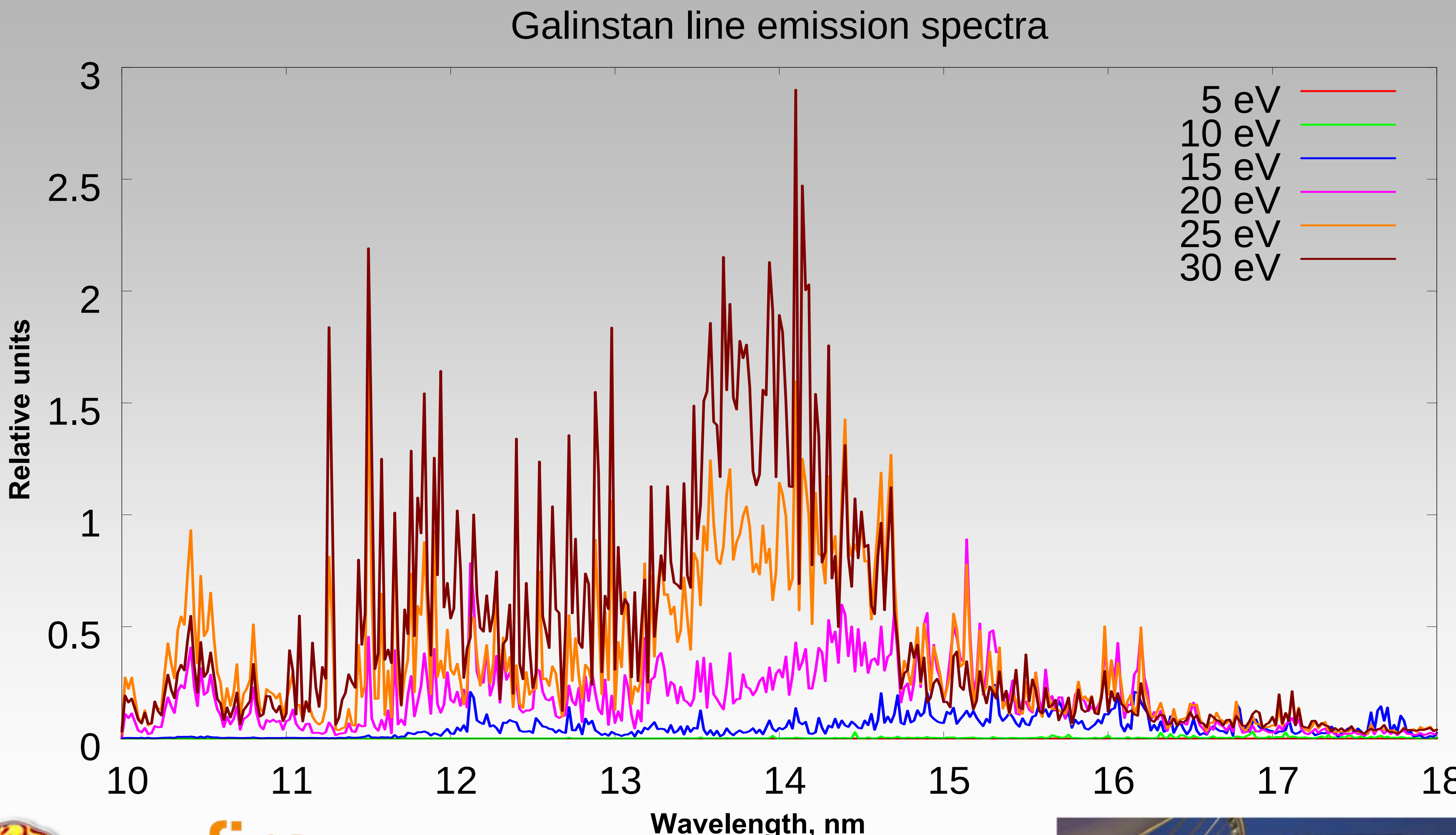
Calculated EUV spectra



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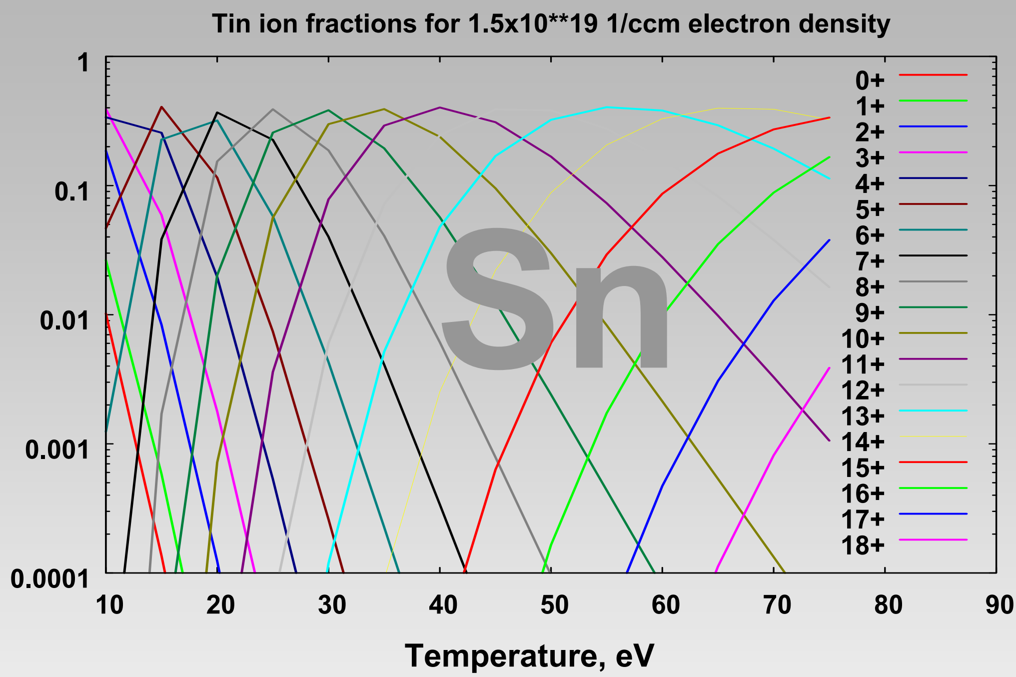
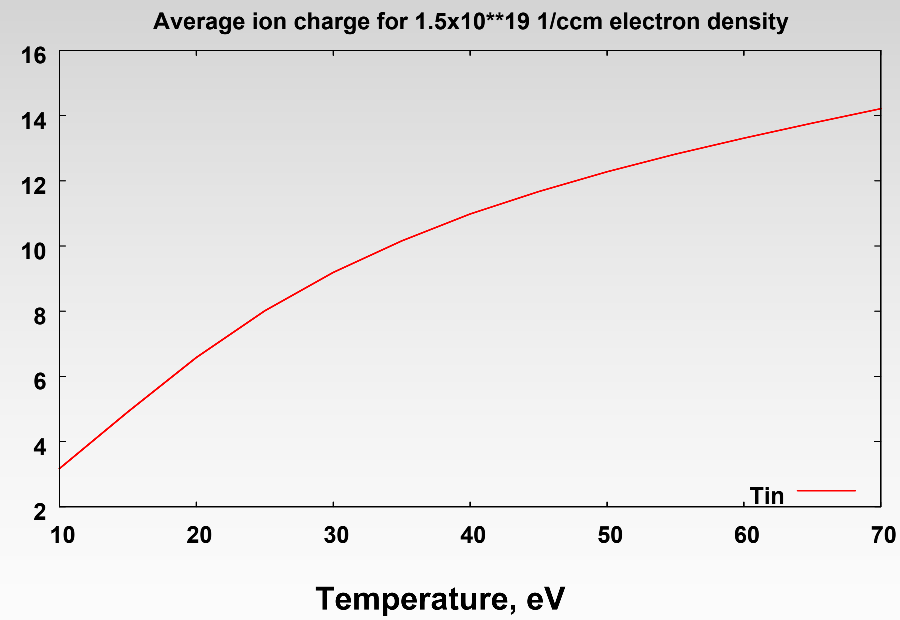
Ion fractions and average charge





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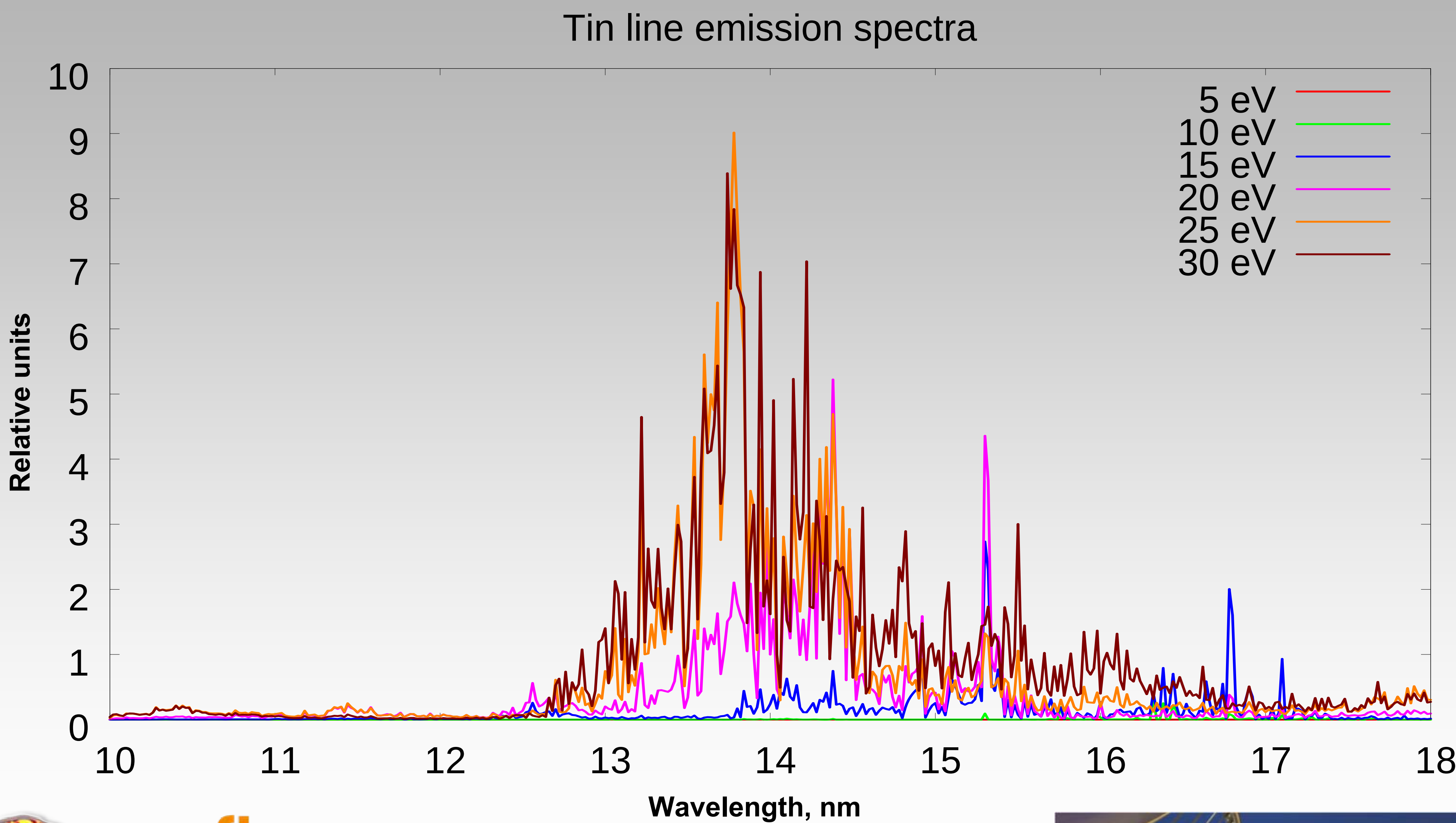

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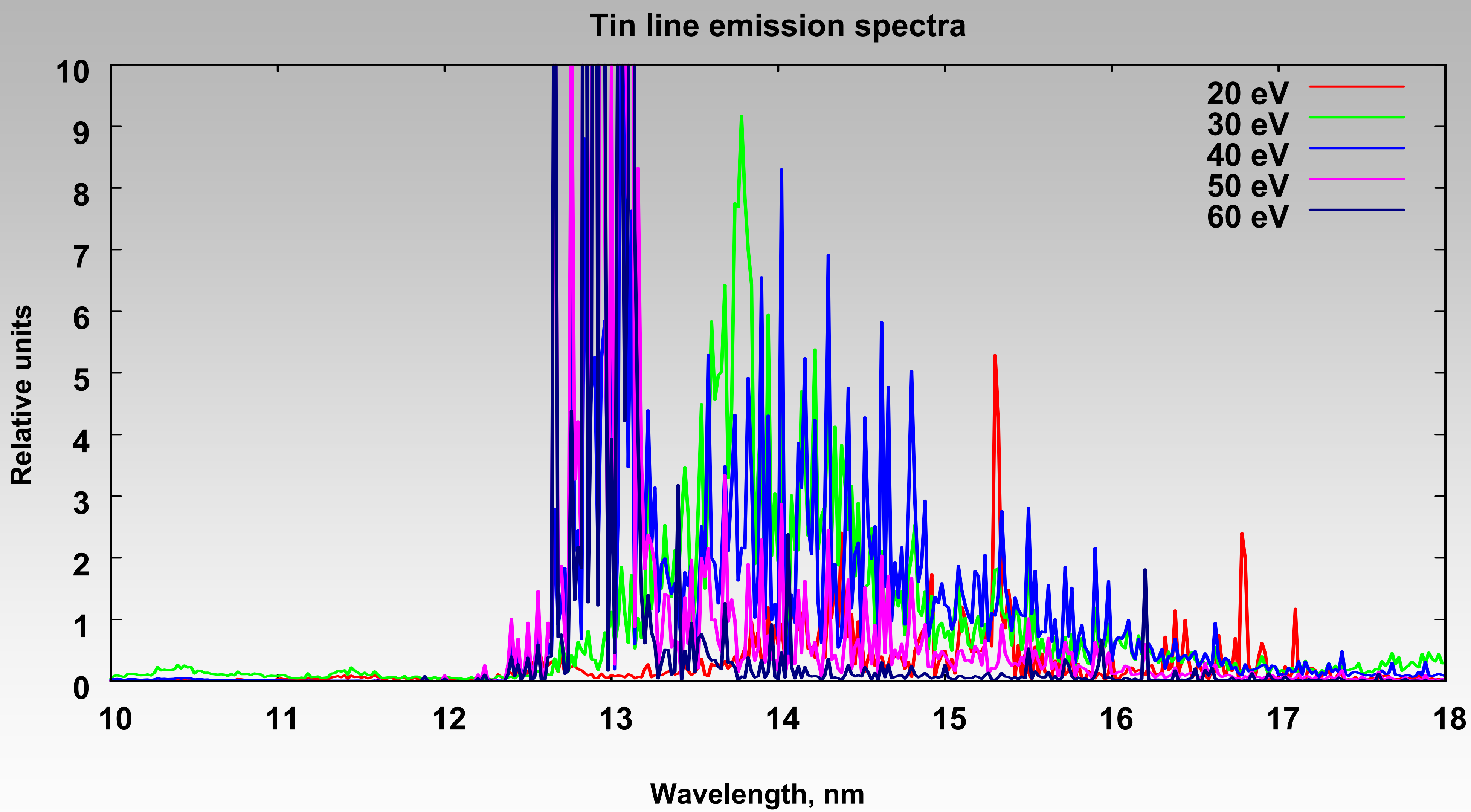
Calculated EUV spectra



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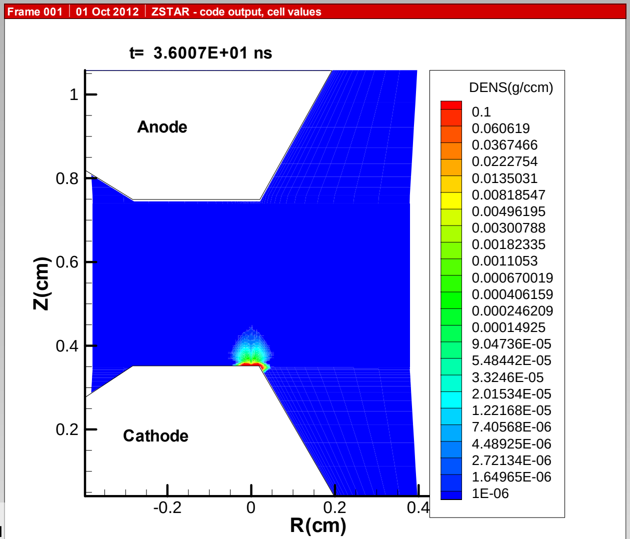
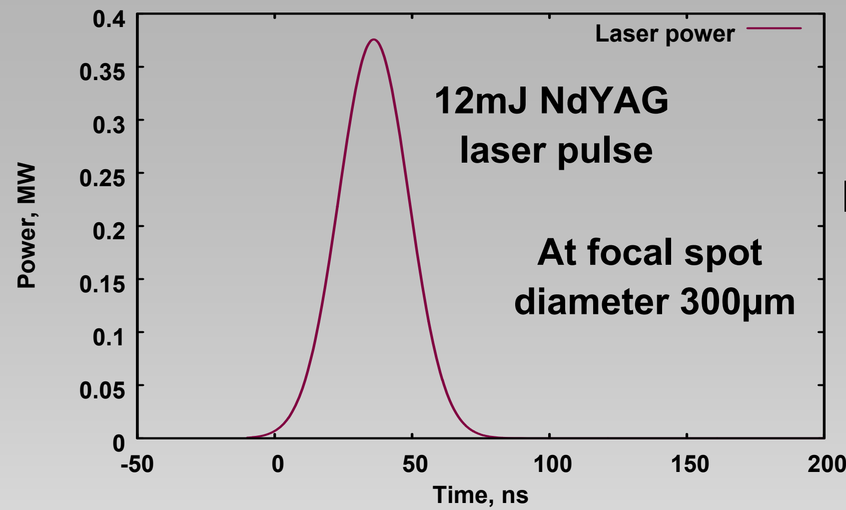
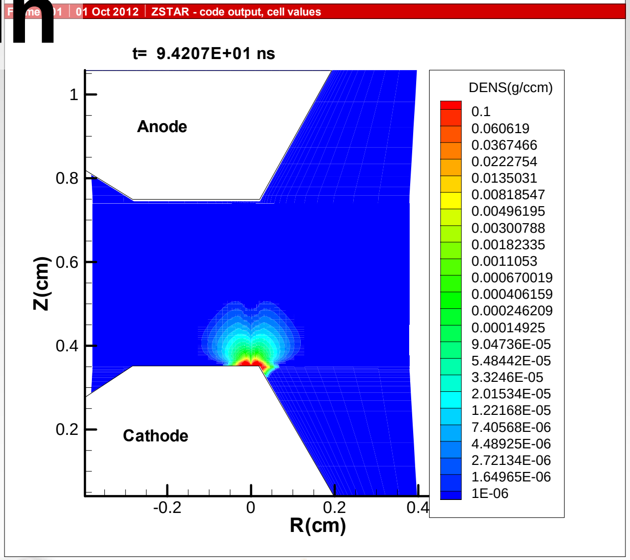
Z* : laser ablation dynamics

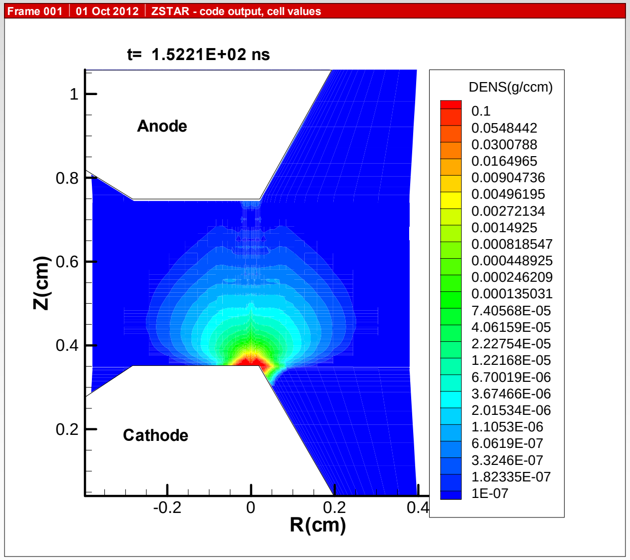


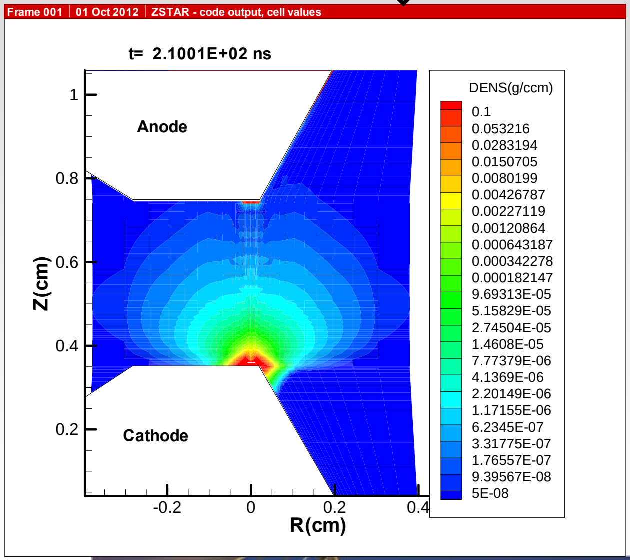


To the time moment 210ns (174ns after laser power maximum) the plasma density near the anode and its conductivity become high enough for discharge ignition

tin







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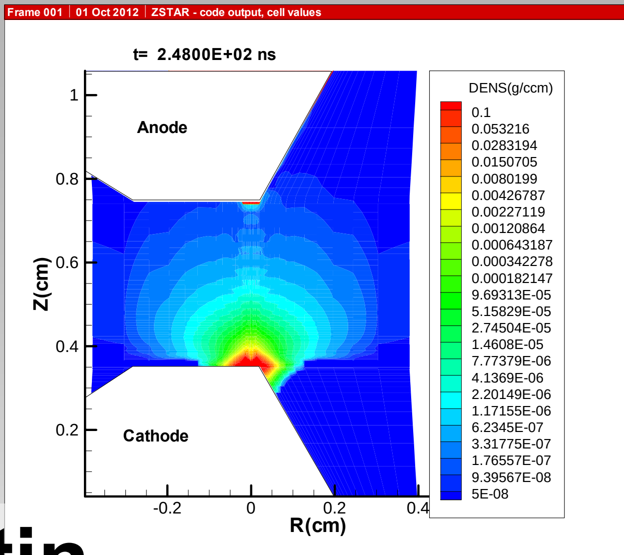
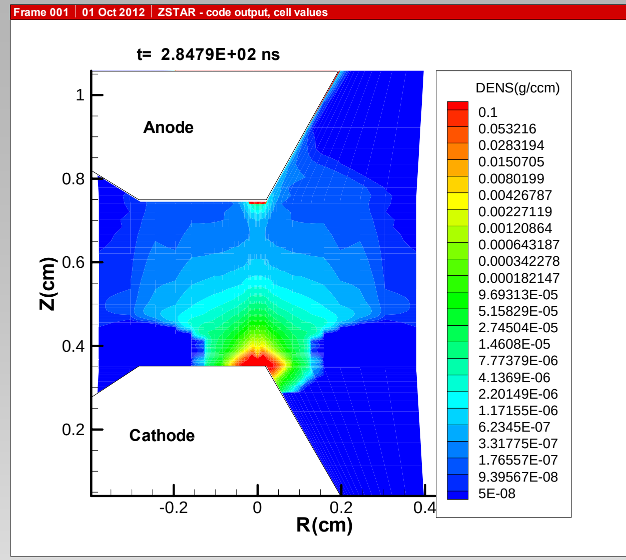
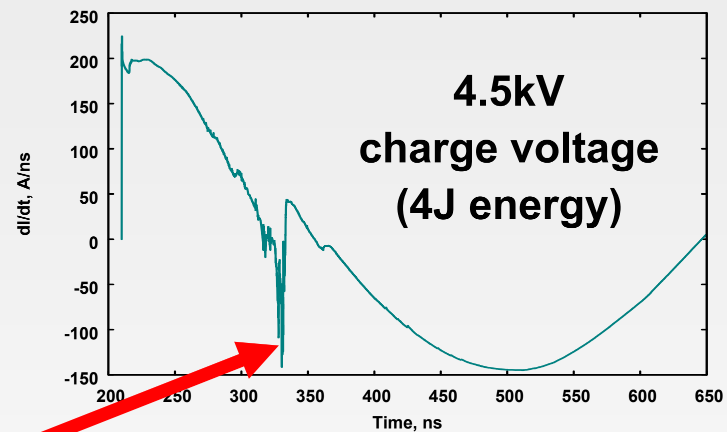
Z* modelling: pinch dynamics

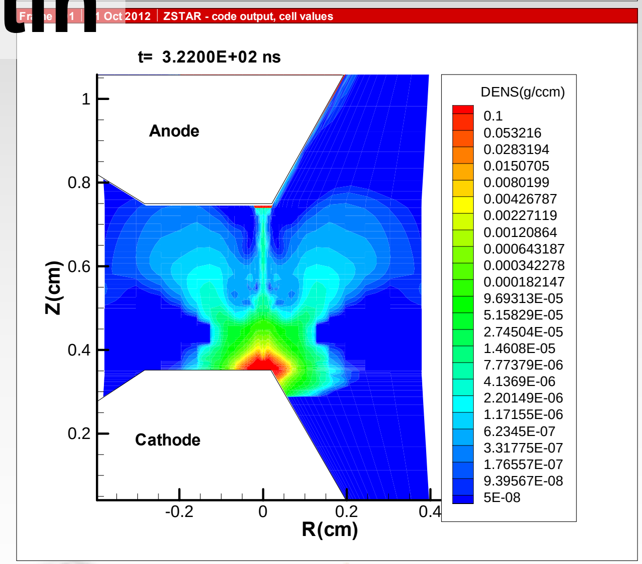
tin



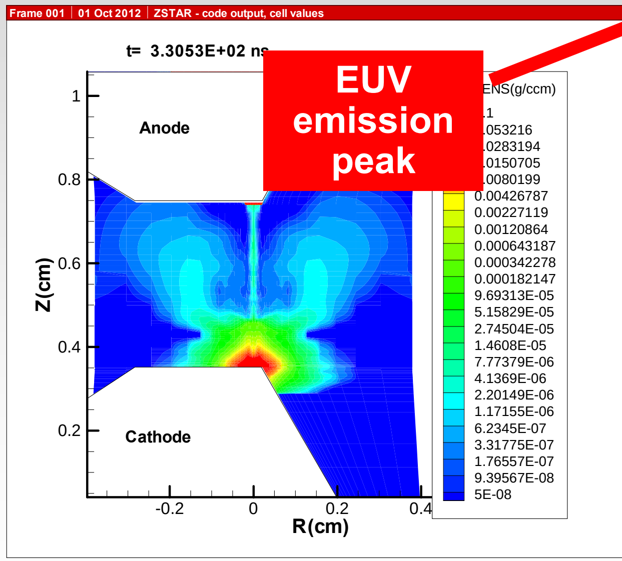


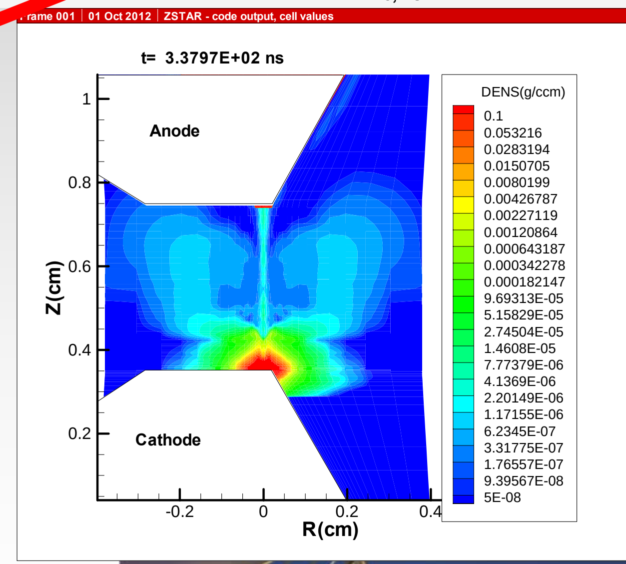
Calculated dI/dt demonstrates pinching





EUV emission peak





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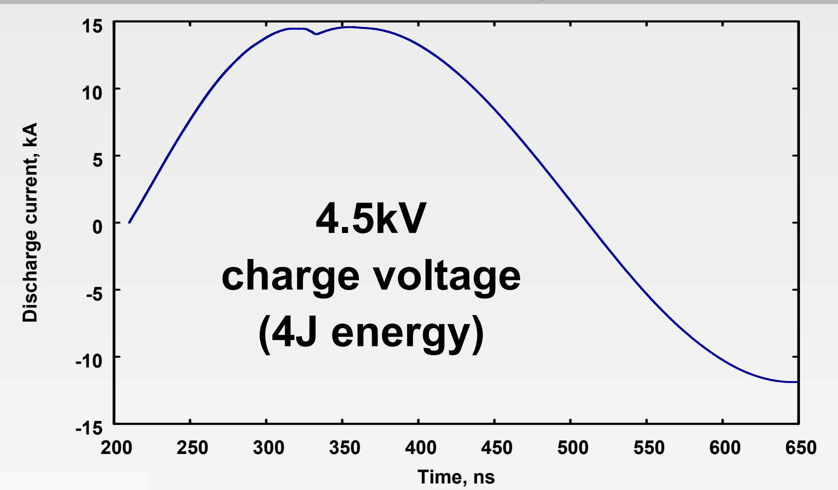
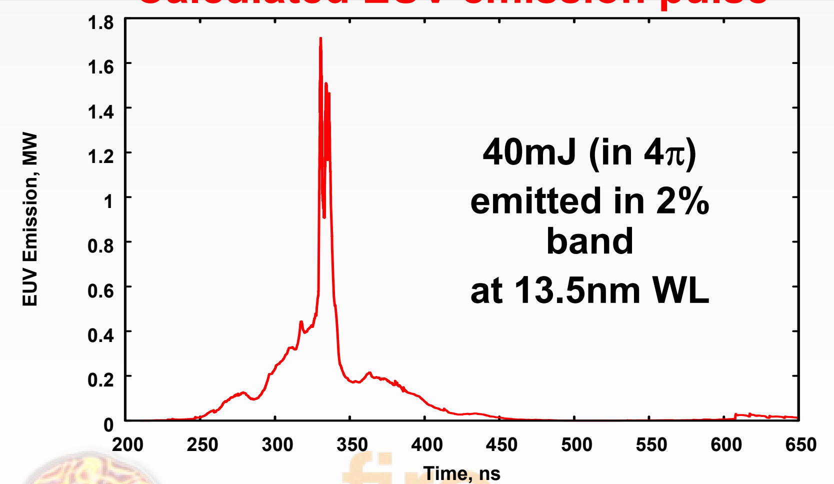
Z* modelling: EUV emission

Calculated discharge current



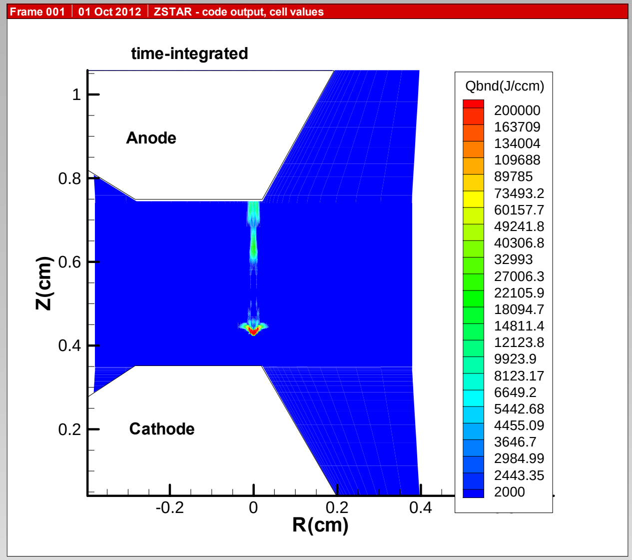
tin

Calculated EUV emission pulse

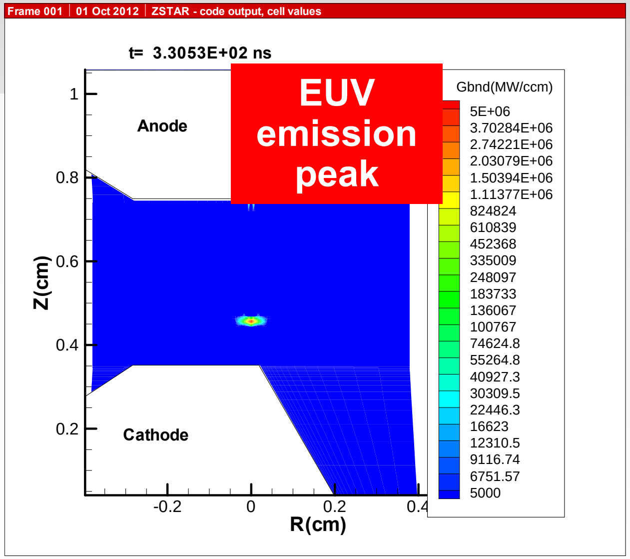


EUV radiation source images

Time - integrated



Instantaneous



In the emission maximum

N_e=1.4-1.6·10^{19} cm^{-3}

T_e=30-60eV

<Z>=10-13

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Conclusions

- EUV emission from Laser Assisted Vacuum Arc (LAVA-lamp) discharge in Galinstan and Tin vapor investigated experimentally is compared with simulations.

- EUV imaging – pinch is smaller ~100 µm in diameter
- Tin in-band emission is more efficient than from Galinstan (by a factor of 5x) mainly due to higher spectral efficiency.
- Gallium ions are mainly responsible for EUV emission below 13 nm whereas Indium ions emission dominates in the spectrum above 14 nm.
- Tin discharge is more reproducible than in Galinstan due to higher plasma conductivity at the breakdown.
- Pinching time matching to the current maximum is significant for the high EUV output and is sensitive to the trigger laser energy.
- Comparison with calculated discharge dynamics in Galinstan is ongoing.

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